

## Analysis of the Acoustic Response of a Railroad Bridge

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**Abstract:** Aging infrastructure (e.g., railroad bridges) requires frequent inspections to assess their structural integrity. However, the large amount of existing infrastructure, and the distance between these structures present significant challenges to inspectors. A simple, method to monitor the structural integrity of infrastructure is needed. Acoustics-based technologies represent a simple, and relatively inexpensive, technique to monitor the integrity of a structure. To develop these techniques, designers must understand the frequencies and sound pressure levels that develop from a typical bridge structure. Infrasound is acoustic energy whose frequency is below that of human perception. Large infrastructure, such as bridges, emits such signals at their natural or driven frequencies of vibration, providing an indication of the structural condition. The feasibility of this type of monitoring was recently evaluated during an in-service load test of a single through-truss railroad bridge at Ft. Leonard Wood, MO, in conjunction with local infrasound monitoring.

**Keywords:** Acoustic, structural integrity, infrasound.

### 1. Introduction

Infrasound is low frequency sound waves between 0.1 to 20 Hz. Since typical human hearing ranges from 20 Hz to 20,000 Hz, humans do not hear infrasound. There are many sources of infrasound including volcanoes, earthquakes, bolides (meteors), man-made explosions, mining explosions, atmospheric explosions, surf, missiles, rockets, weather systems and even animal vocalizations [1].

In order for up-going infrasonic energy to be observed at Earth's surface, it must reach an area of higher sound velocity than at the point of origin. If this occurs the energy turns and then returns to the surface of the earth. Temperature strongly affects the effective sound speed. Thus,

the temperature variation through the atmosphere determines if infrasound energy returns to Earth's surface. Figure 1 shows the sample effective sound speed profile with the regions of the atmosphere labeled.

Large man-made structures, such as bridges, have been reported to generate infrasound [3,4]. However, little research has been done into the diagnostic possibilities in the data recorded near these structures; Donn [3] was unable to discern the source driver for the infrasound generated by the bridge. It is likely that these infrasound signals contain information about the natural modes of vibration of the infrastructure. Thus, infrasound monitoring of structures may provide a future methodology for assessing the condition of significant infrastructure. Given the complexity of developing this assessment methodology, computational modeling can provide valuable insight into how infrasound develops and propagates. The development of an acoustic source model of a structure provides an important first step for developing this modeling methodology.

The development effort described in this paper seeks to produce a model of the Ft. Leonard Wood railroad bridge that will be an infrasound source for a larger atmospheric model.

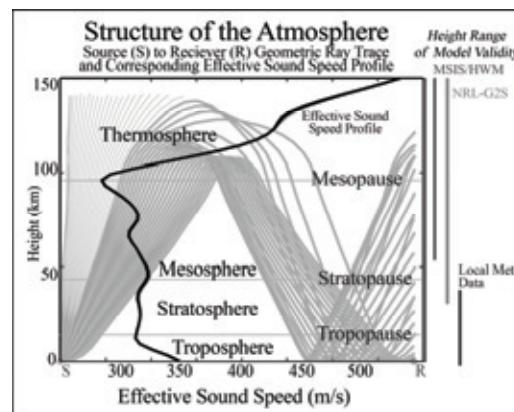


Figure 1. Idealized atmospheric structure [2].

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14. ABSTRACT <b>Aging infrastructure (e.g., railroad bridges) requires frequent inspections to assess their structural integrity. However, the large amount of existing infrastructure, and the distance between these structures present significant challenges to inspectors. A simple, method to monitor the structural integrity of infrastructure is needed. Acoustics-based technologies represent a simple, and relatively inexpensive, technique to monitor the integrity of a structure. To develop these techniques, designers must understand the frequencies and sound pressure levels that develop from a typical bridge structure. Infrasound is acoustic energy whose frequency is below that of human perception. Large infrastructure, such as bridges, emits such signals at their natural or driven frequencies of vibration, providing an indication of the structural condition. The feasibility of this type of monitoring was recently evaluated during an in-service load test of a single through-truss railroad bridge at Ft. Leonard Wood, MO, in conjunction with local infrasound monitoring.</b>					
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Figure 2. Bridge 0.3 on Ft. Leonard Wood

## 2. Modeling Methodologies – COMSOL Multiphysics

Developing the acoustic source model for a bridge requires two physics; structural vibration and acoustic wave propagation. Given the two physics in this source model, COMSOL Multiphysics provides an ideal platform for developing this source model.

For structural vibration, the railroad bridge at Ft. Leonard Wood, as shown in Figure 2, can be represented using beam elements. Thus, the use of three-dimensional beams requires that the Solid Mechanics Module provided the computational capabilities to calculate the structural vibration of the bridge. The calculations were conducted using an eigenfrequency analysis application mode.

First, a model was constructed to calculate the natural frequencies and mode shapes of the bridge. The modal analysis is based on the data collected during the load rating portion of the field experimentation. Beam elements provided the basis for modeling the structure in this model. Section properties were assigned to each beam element as specified in Table 1

Figure 3 shows the location of each section specified in Table 1 **Error! Reference source not found.** Figure 4 shows the finite element model constructed in COMSOL. The model is constrained by pins at both ends of the bridge.

With the vibrational characteristics of the bridge defined, a second model to calculate the acoustic response of the bridge was developed. For the acoustic analysis, the pressure acoustics application mode from the acoustics module was used. Although COMSOL does support meshing of lines, these “beam” elements represent a poor choice for the acoustic model due to their lack of free surfaces that produce acoustic waves as the structure interacts with the air. To include the effects of the surface area of the beams, the acoustic model represents the beams as hollow rectangles that encompass the outer parameter of the beam. These equivalent sections produce the acoustic response of the bridge during vibration.

With the acoustic-structure interaction developed for the bridge, the next step was to include the surrounding terrain for the bridge. Ten meter National Elevation Dataset data was used for the topography profile, provided by the USGS. Figure 5 shows the local topology for a 500 m square that centers on the bridge. The white region that runs across the square is the river bed over which the bridge is built.

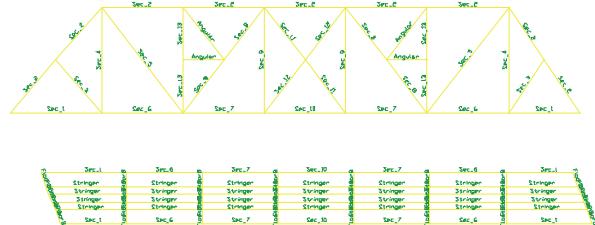


Figure 3. Elevation and plan view of bridge at Ft. Leonard Wood showing section names provided in Table 1.

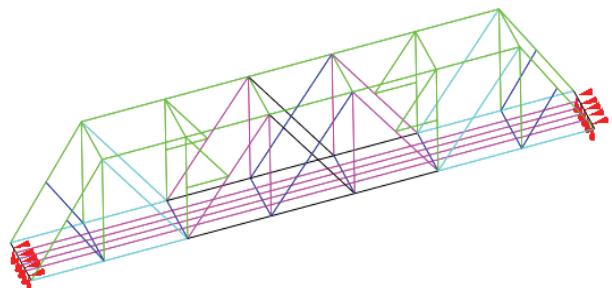


Figure 4. Finite element model constructed using COMSOL Multiphysics.

Table 1. Section properties for Bridge

Section	Area (in^2)	Torsional Constant (in^4)	Moment of Inertia 3-3 (in^4)	Moment of Inertia 2-2 (in^4)
1	24.125	16.806	88.599	1655.393
2	48.832	13.058	2593.331	2024.503
3	6.125	0.131	53.253	255.188
4	21.938	6.769	177.817	122.856
5	21.000	13.852	85.750	891.188
6	24.125	16.806	88.599	1655.393
7	42.000	27.705	171.500	2124.938
8	16.422	0.924	338.938	617.545
9	12.250	1.725	224.724	36.162
10	42.000	27.705	171.500	2124.938
11	7.250	0.331	30.432	355.182
12	7.250	0.149	36.120	181.882
13	6.750	0.143	149.038	36.047
Stringer	35.500	8.763	8019.458	98.490
Angular	3.875	0.081	2.876	58.416
Floor Beam	46.500	14.785	15351.375	166.219

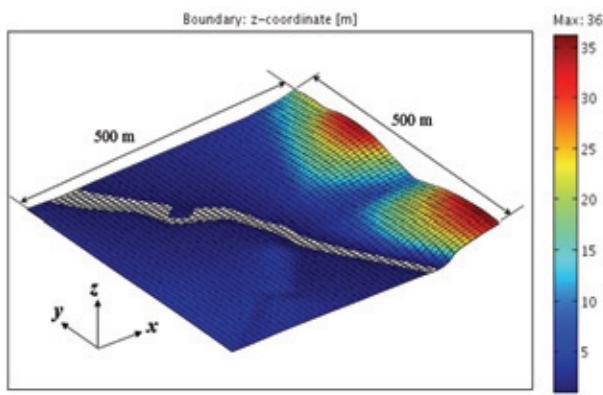


Figure 5. Local topology for a 500 m square centered on the bridge.

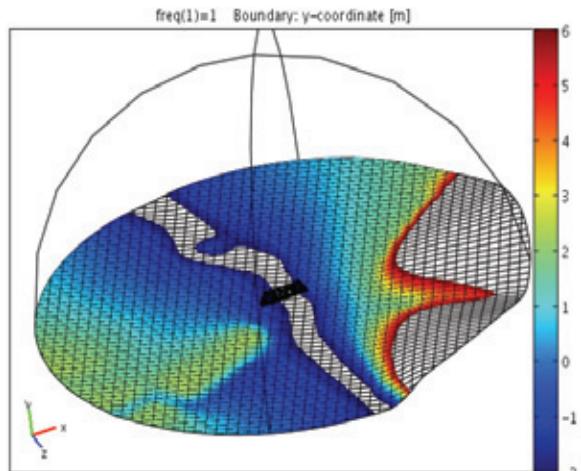


Figure 6. Local topology for a hemispherical region with radius of 500 m around the bridge.

To incorporate the terrain into the acoustic model shown in Figure 5, a hemisphere with a radius of 500 m was mapped onto the available topological data, as shown in Figure 6. This model provides the acoustic response of the bridge as it interacts with the local topology. These models assume the sound reflects perfectly off the topography without any impedance.

### 3. Results and Discussion

The eigenfrequency analysis conducted in COMSOL shows a resonant frequency of the bridge at 2 Hz that should produce significant acoustic energy. Thus, the acoustic analyses focus on the 2 Hz vibration.

By using the simplified geometric model of the bridge, the distribution of acoustic energy from a 2 Hz vibration of the bridge can be calculated. Figure 7 shows the distribution of sound pressure level developed from the vibrating bridge model as it interacts with the local topography. Figure 8 shows the sound pressure distribution for the same 2 Hz bridge vibration as it reflects off a planar surface. The effect of local topographic details is clearly shown by comparing the sound pressure levels along a circumferential arc in Figure 9. These results clearly show a small perturbation of the sound pressure levels due to the local topography.

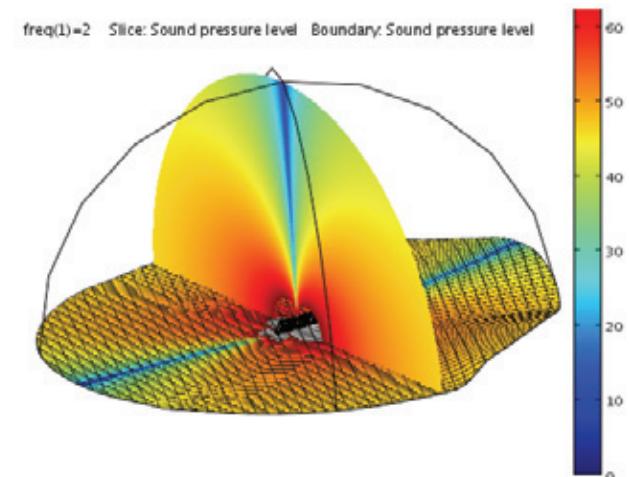


Figure 7. Sound pressure distribution developed from bridge as it interacts with topography.

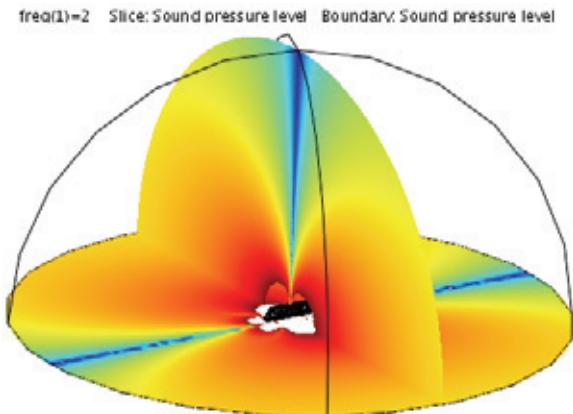


Figure 8. Sound pressure distribution developed from bridge as it interacts with a planar topography.

## 7. Conclusions

This work shows the use of COMSOL Multiphysics to predict the vibrational modes of a complex structure and the use of these vibrational modes as an acoustic source.

Initial source modeling indicates that the bridge functions as a directional source, with energy propagating along the river bed, perpendicular to the direction of traffic with minimal effect of topography. Further study will include synthesis of the meteorological data from the multiple on-site stations to create a four-dimensional, time-dependent atmospheric space.

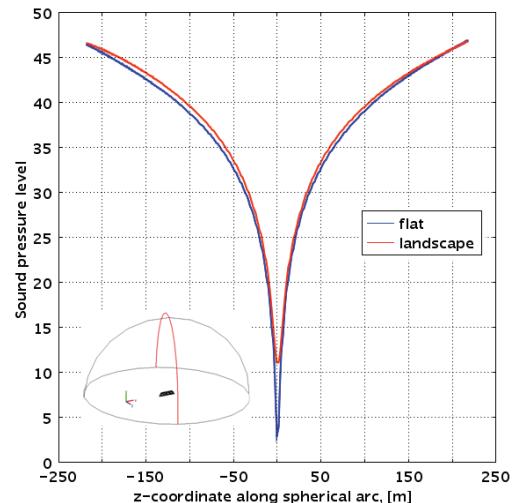


Figure 9. Comparison of sound pressure levels for actual and planar topography for the arc indicated in the figure.

## 8. References

1. Bedard, A. J. and T. M. Georges. Atmospheric Infrasound. *Physics Today*. March, (2000). pp 32-37.
2. McKenna M., B. Stump, S. Hayek, J. McKenna, and T. Stanton. Tele-infrasonic studies of hard-rock mining explosions. *Journal of the Acoustical Society of America*. **Volume 122, Issue 1**, pp. 97-106. (2007) doi: 10.1121/1.2741375
3. Donn, W. Atmospheric Infrasound Radiated by Bridges. *Journal of the Acoustical Society of America*. Vol. 56, No. 5. (1974)
4. Kobayashi, Y. Infrasound generated by a highway bridge. *Butsuri-Tansa* **Vol. 52, No. 1**. pp 54-60. (1999) (in Japanese)

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# **Analysis of the Acoustic Response of a Rail Road Bridge**

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**Dr. Sergei Yushanov (AltaSim)**

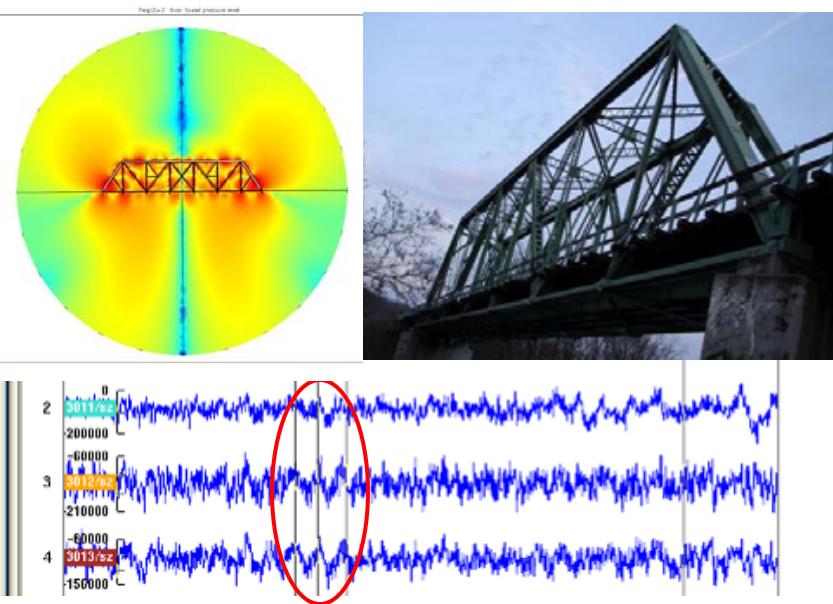
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### Research Objective

1. To experimentally verify that infrasound can monitor the fundamental modes of motion for a Pratt-Truss bridge at ~30 km standoff.
2. To develop a new finite element representation to numerically predict how structures can couple into the atmosphere and propagate infrasound energy at tactical standoff distance.

**Problem:** Remote assessment of infrastructure for reconnaissance or battle damage has historically depended upon satellite imagery or information revealed by boots on the ground.

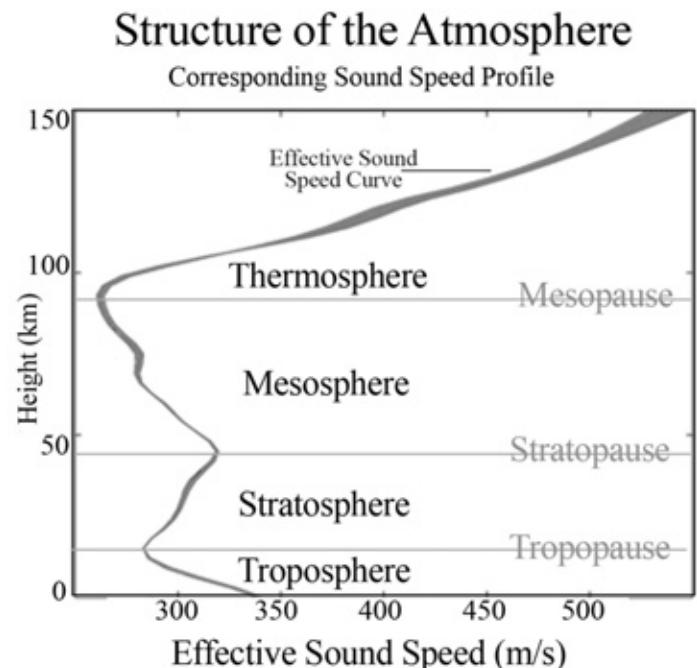
**Solution:** Use infrasound acoustics in combination with seismic, meteorological and audible acoustic methods to determine fundamental modes of movement for bridges without line of site or direct involvement by personnel

### Seismic-Infrasound-Acoustic-Meteorological Array



# What is infrasound?

- Low frequency acoustics ( 0.01 – 20 Hz) created by:
  - Volcanoes
  - Earthquakes
  - Bolides (meteors)
  - Explosions in the atmosphere
  - Sub-surface explosions
  - Surf
  - Missiles
  - Rockets
  - Weather systems
  - Animal vocalizations
  - Urban Noise\*



## PREMISE:

**Structures generate coupled low-frequency acoustics as fundamental modes of motion**

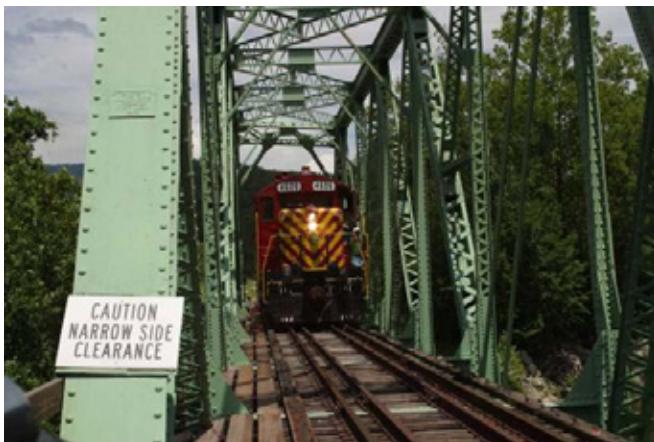
*What is the physics behind these signatures?*

*How far do they propagate? Under what conditions?*

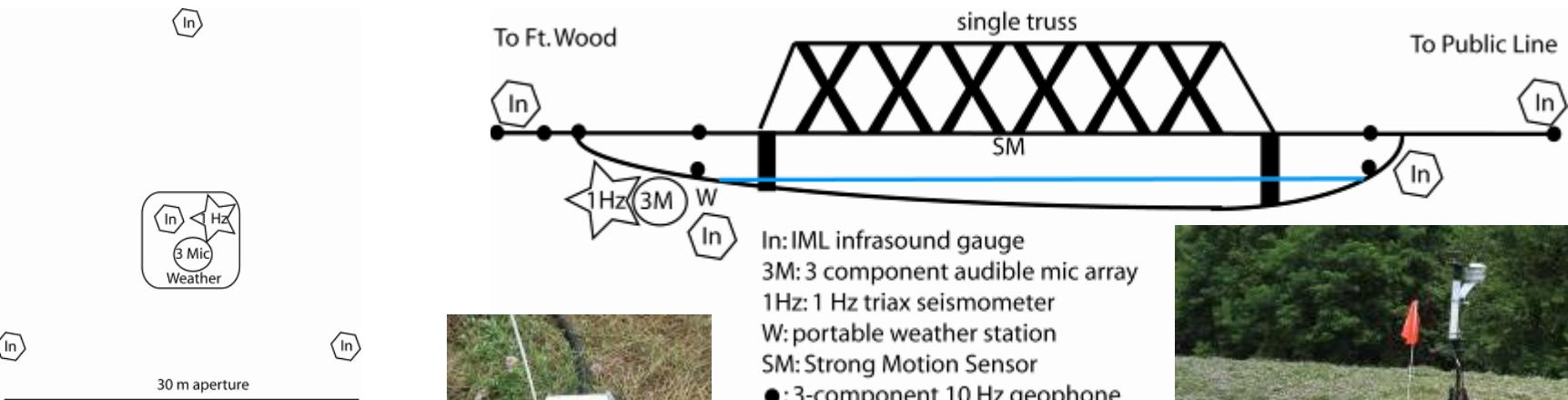
*What can you measure/assess about the structure given the acoustic information?*

### Geophysical Data Collection

- 3 arrays: seismic, infrasound, acoustic and meteorological sensors (SIAM arrays). Infrasound gauges produced for this project by Intermountain Laboratories (IML)
- 5 balloon launches for weather data at receiver array
- Network of on-post met monitoring sites.
- 2 75-ton engines, 8 flat cars



Array deployed at target bridge



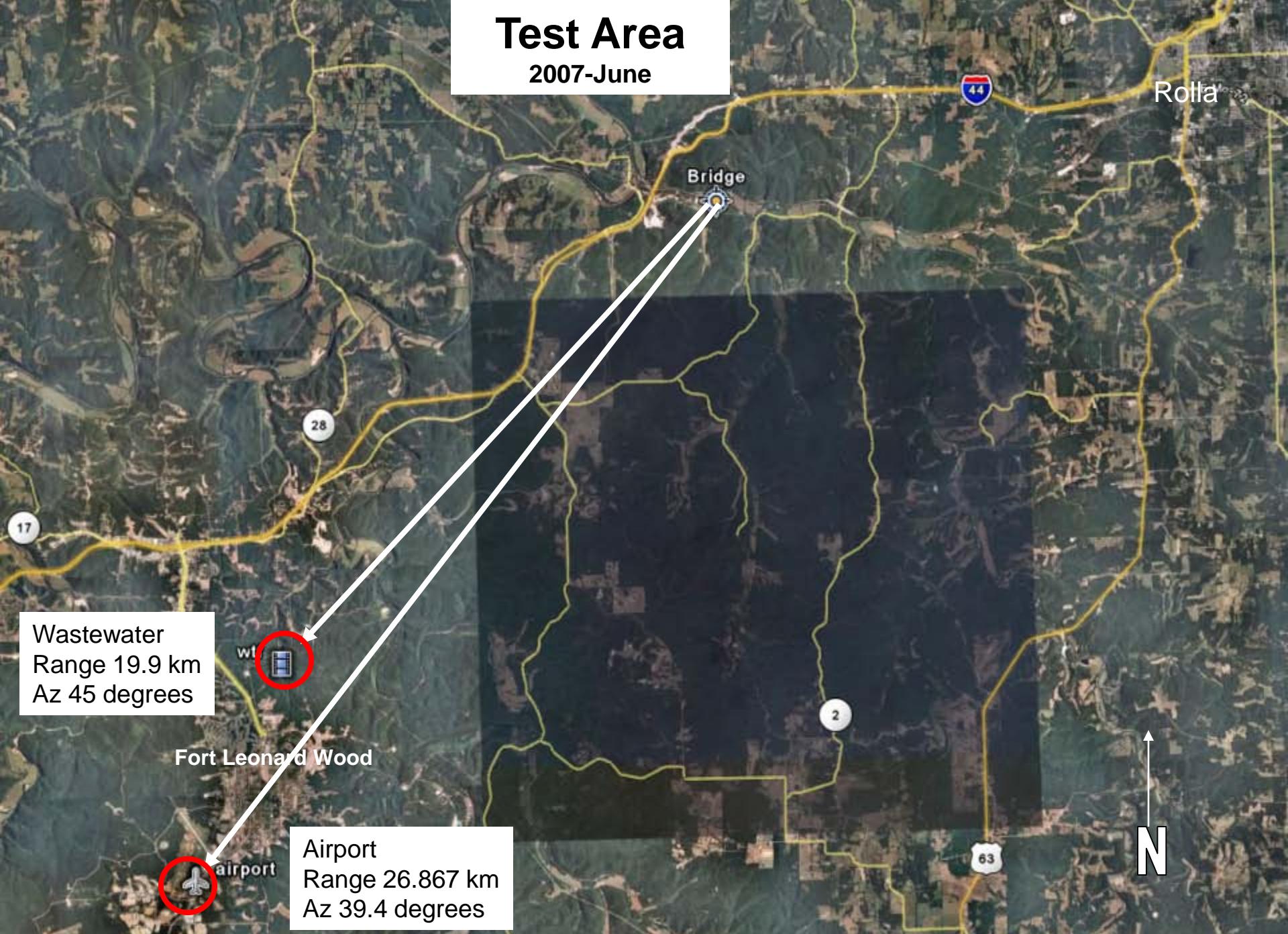
2 standoff arrays

In: IML infrasound gauge  
 3 Mic: 3 component audible mic array  
 1 Hz: 1 Hz seismometer  
 Weather: portable weather station

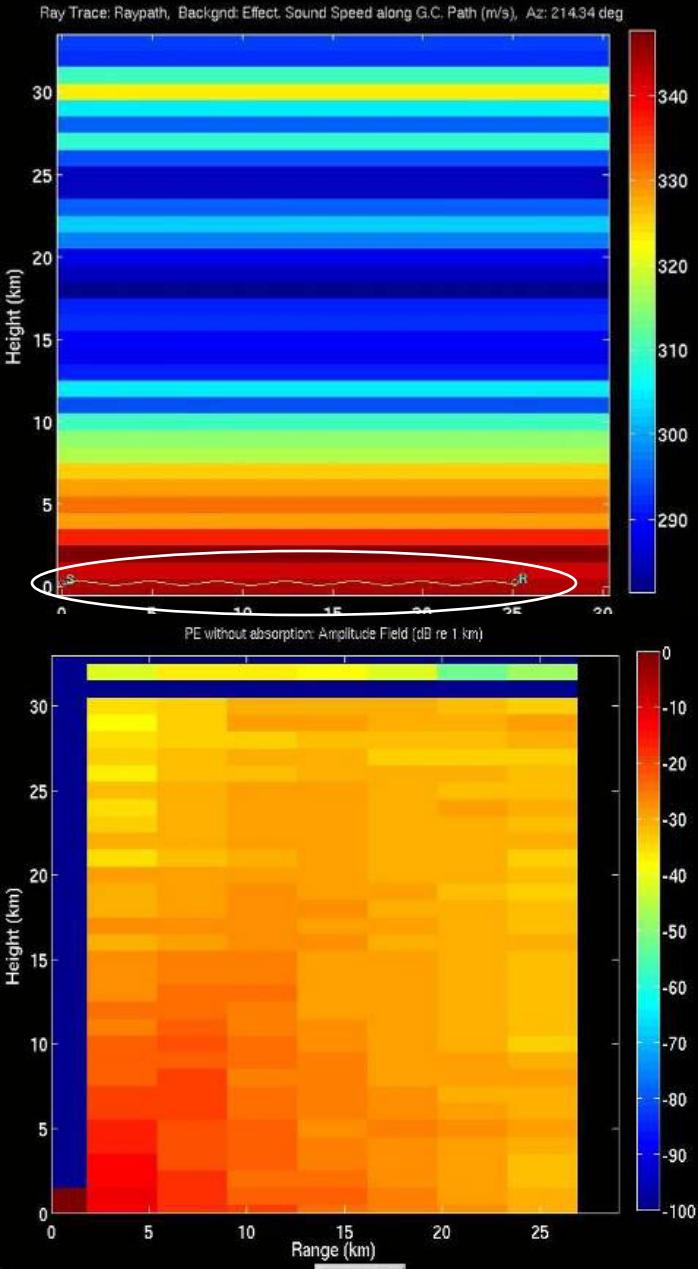


# Test Area

2007-June



Ray Trace: Raypath, Background: Effect. Sound Speed along G.C. Path (m/s), Az: 214.34 deg

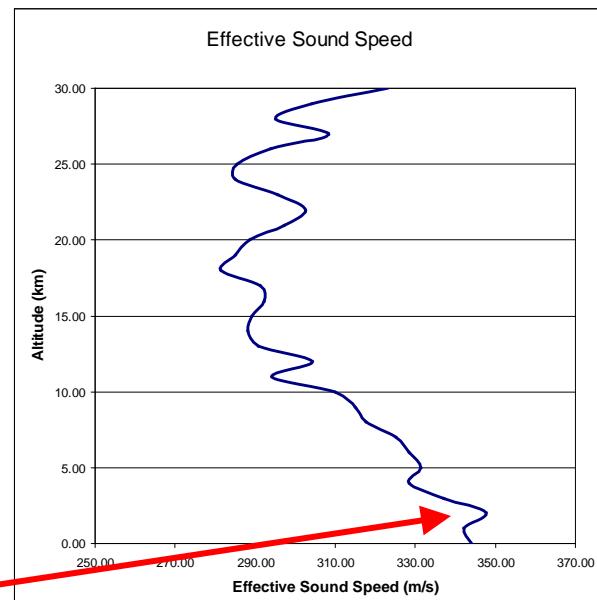
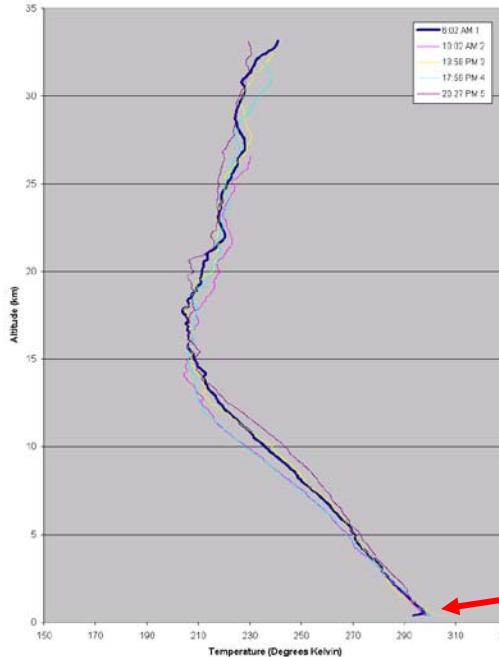


Effective Sound Speed (m/s)

dB loss relative to 1 km

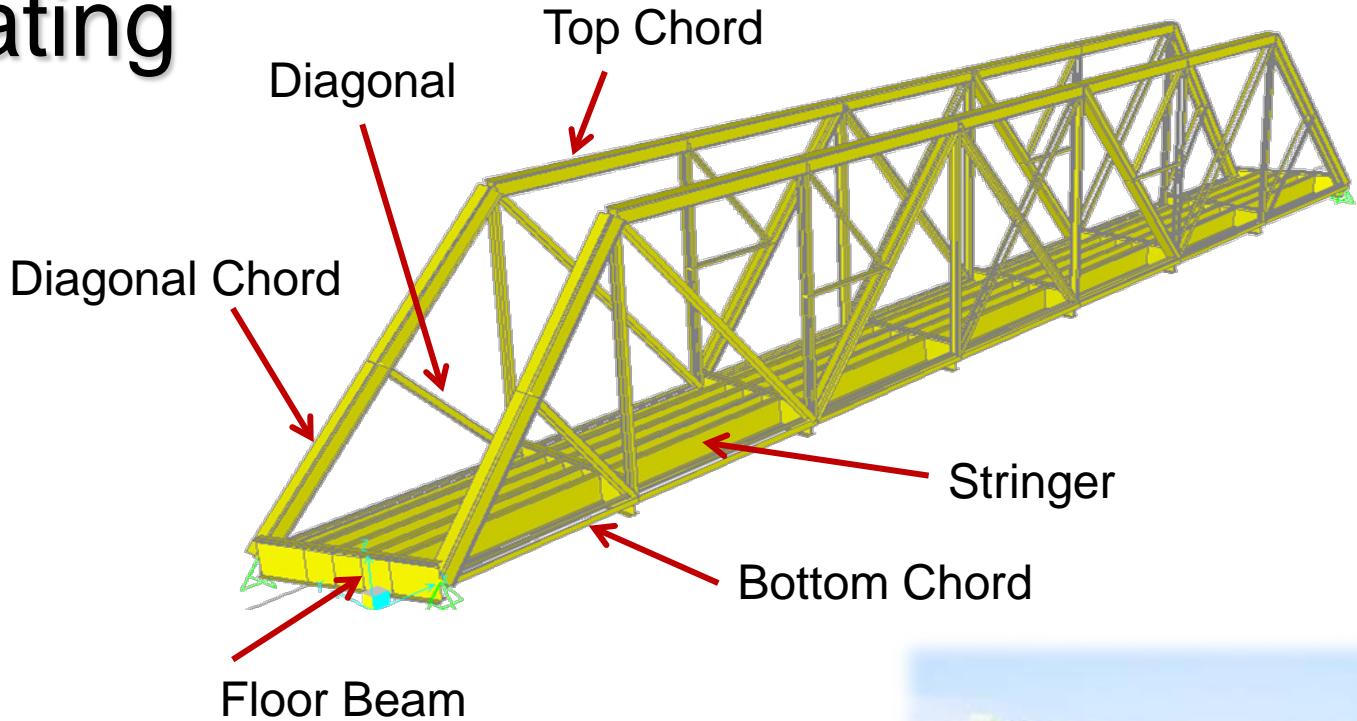
## Propagation Modeling

- Data analysis searching for the bridge signature initially focused on the time window from 4 AM to 8 AM local time.
- Numerical modeling of the Radiosonde data predicted only one successful arrival (at 6AM local time).



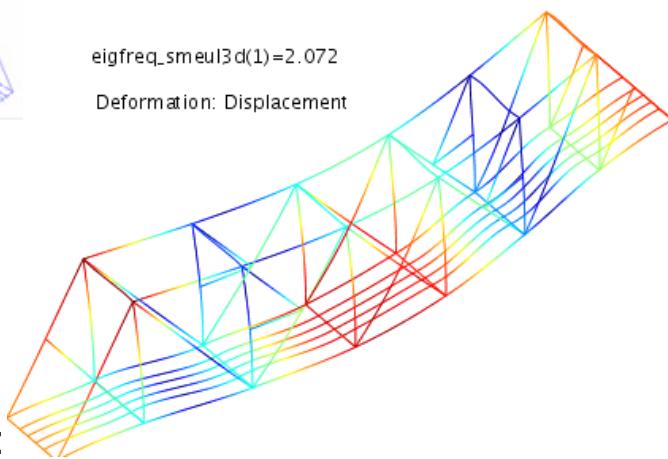
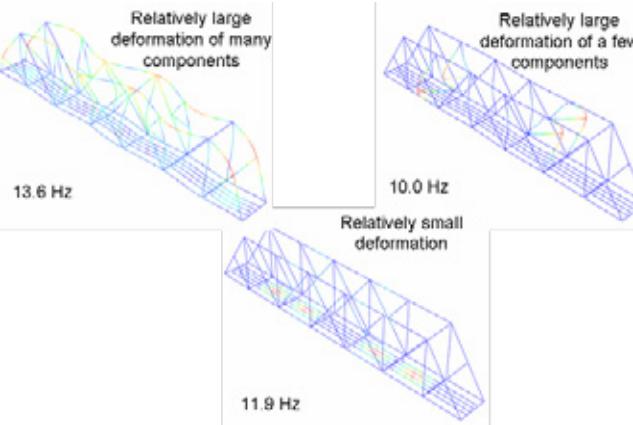
# Load Rating

- **Experimental load rating tests:**
  - **Strain Gages (44 Used)**
    - Main Structural Elements
  - **One Train Engine**

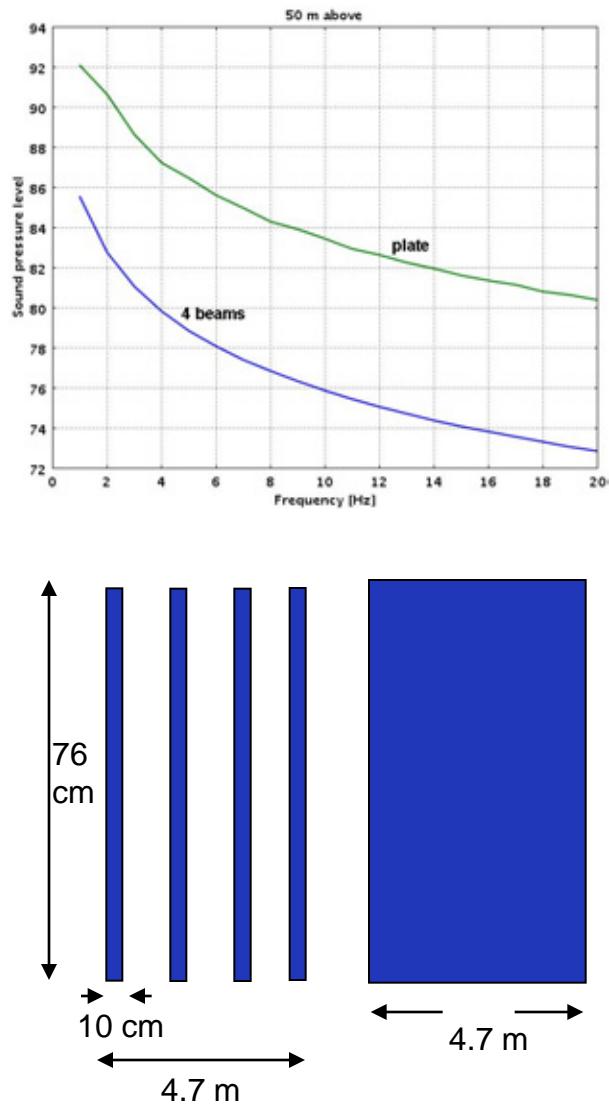


# Modal Analysis: COMSOL

- Key components :
  - Required a simplified source to limit computational costs
  - Accurate representation of the acoustic energy emitted

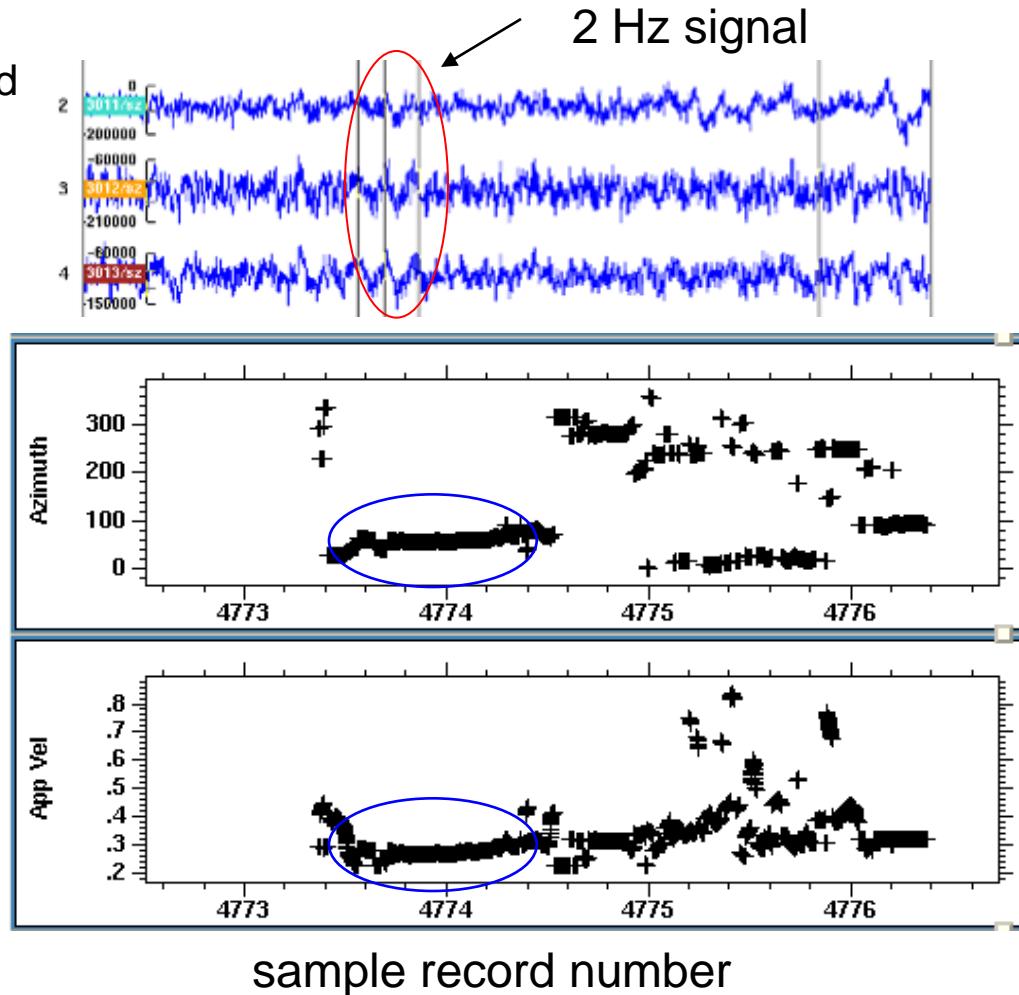
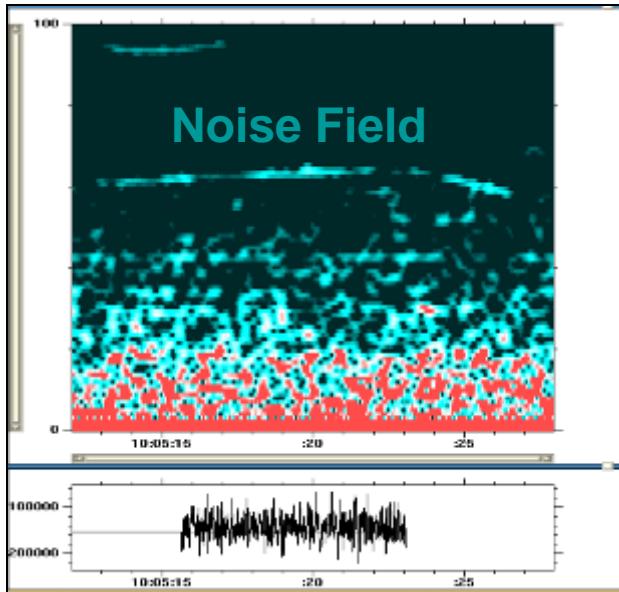


- Technical Hurdles overcome:
  - Beam/truss elements can be represented as point sources
  - Geometry of beams important for acoustic response
  - no single area dominates acoustics

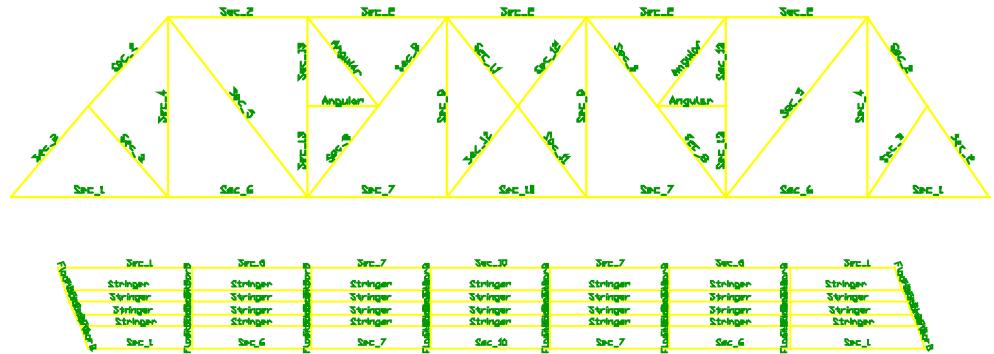


# Infrasound Bridge Signal

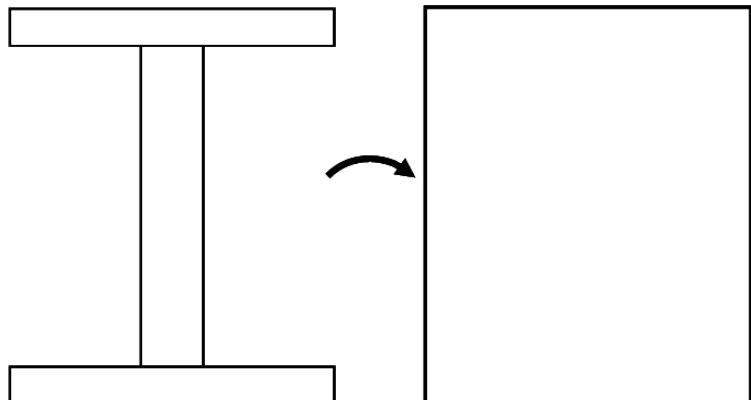
- Bridge signal was seen at both remote arrays.
- fK (frequency-wave number) analysis results correspond with bridge azimuth and infrasound passband/phase velocity.
- Includes fundamental mode frequencies of interest (2, 6 and 13hz) - extremely low amplitude signal and difficult to tease from the background noise.



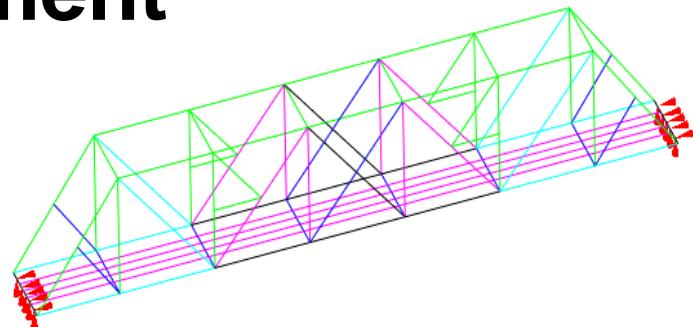
# Model Development



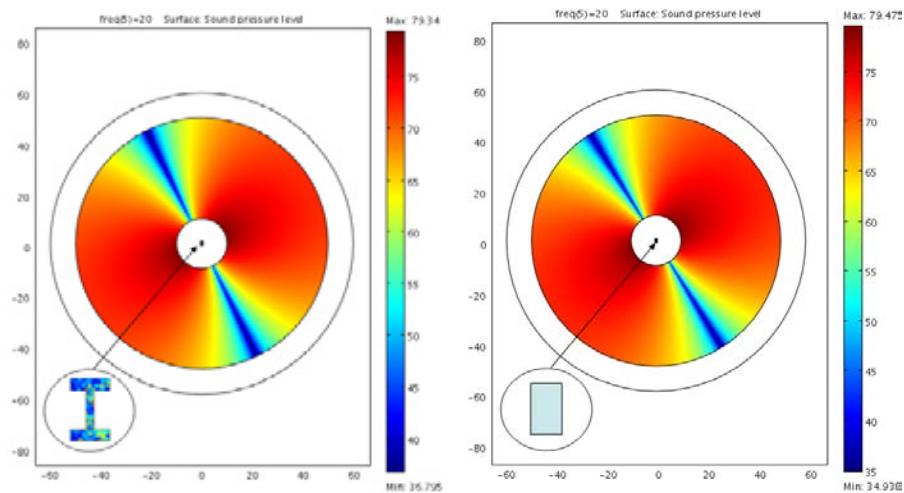
**Figure 1.** Elevation and plan view of bridge at Ft. Leonard Wood showing section names corresponding to the model produced in the load rating.



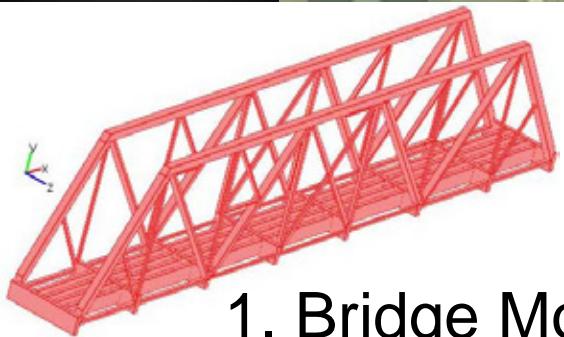
**Figure 3.** Equivalent section used for acoustic analysis.



**Figure 2.** Finite element model constructed using COMSOL Multiphysics.

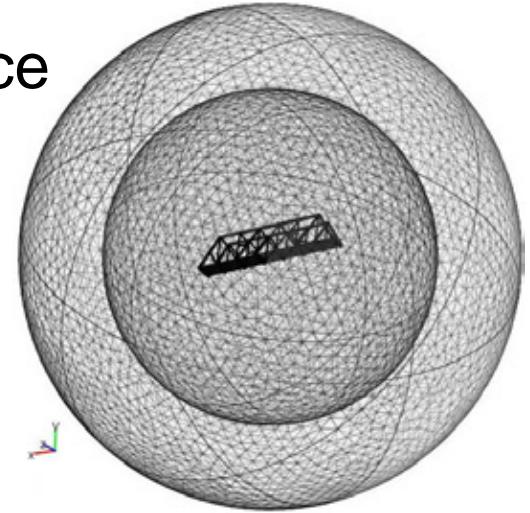


**Figure 4.** Acoustic Assumption. Comparison of sound pressure levels from detailed model of I-beam and rectangle that encompasses outer dimensions of I-beam. Inner area around section has been removed to show details of far-field solution.

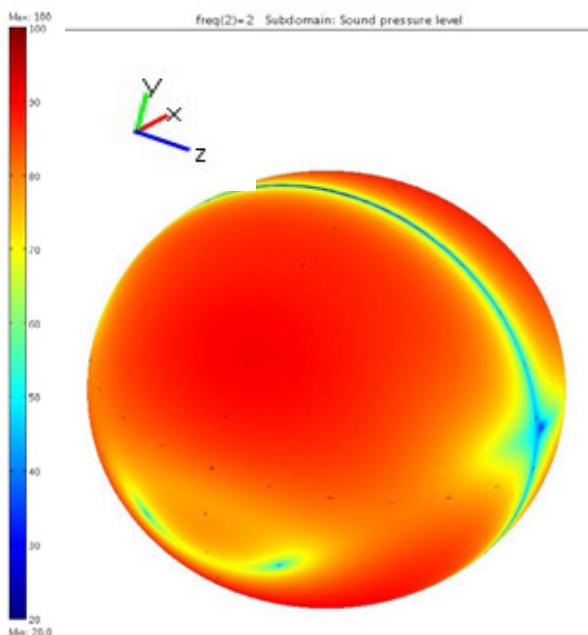


1. Bridge Model

2. Mesh Space

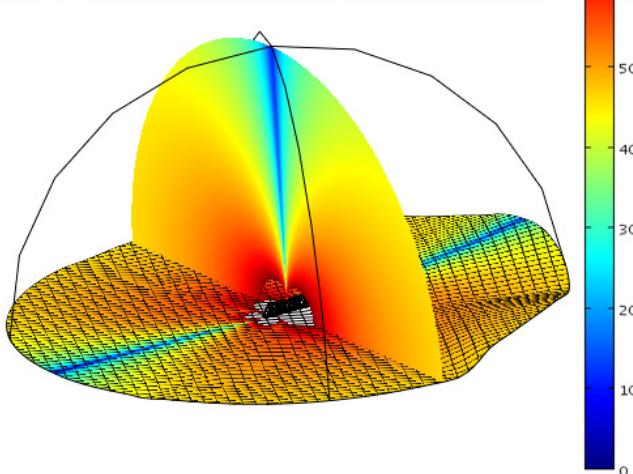


2 Hz  
dominant  
frequency  
shown



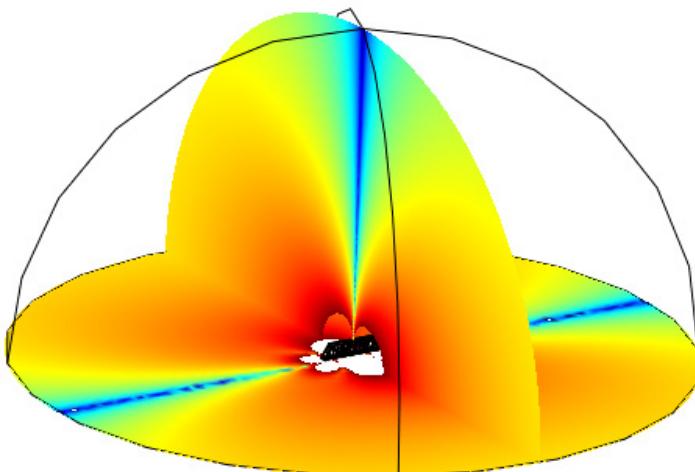
3. 3-D  
Acoustic  
Coupling

freq(1)=2 Slice: Sound pressure level Boundary: Sound pressure level



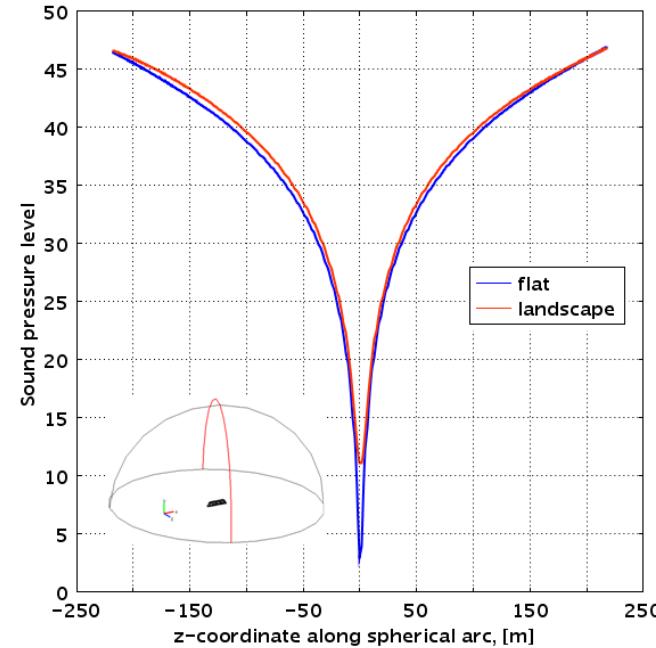
With 10 m topography

freq(1)=2 Slice: Sound pressure level Boundary: Sound pressure level



Flat Earth

## Far-Field Radiation Pattern: Inrasound Source



The acoustical radiation pattern at 50 m can be a representative infrasound source to insert into propagation modeling packages. At 500 m, the source is affected by topography (top left), though in this case, the residual topography effect is small but asymmetric (above).

# Conclusions

- The bridge was observed using infrasound arrays from approximately 20 km, verifying the COMSOL modal modeling.
- Initial source modeling indicates that the bridge functions as a directional source, with energy propagating along the river bed, perpendicular to the direction of traffic, affecting visibility under varying meteorological conditions, though with minimal effect of topography.
  - Though the topographic contribution to propagation was minimal for *this scenario*, more extreme topography in more geophysically complex areas would likely have more impact on the representative source.
- The use of infrasound to monitor structures deserves further study. While a rail bridge was selected for this test case, large dams, cables that suspend cable-cars, and vehicle bridges should be considered for future work.
- If SIAM arrays could be emplaced in areas of interest, continuous monitoring could give indication into the change in structural health of a target, though *the changes due to wear or active damage would need to be great enough to affect the fundamental modes of the structure*.
- This persistent surveillance technology could be applied to civil cases as well, however, the authors emphasize this is not a 'silver-bullet' approach to domestic structural health monitoring or homeland security applications.